

# Rotation of easy axis in training effect and recovery of exchange bias in ferromagnet/antiferromagnet bilayers

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(Dated: February 2, 2008)

For ferromagnet/antiferromagnet bilayers, rotation of the easy axis has been *for the first time* observed during measurements of training effect and the recovery of exchange bias using FeNi/FeMn system. These salient phenomena strongly suggest irreversible motion of antiferromagnet spins during subsequent measurements of hysteresis loops. It is found that the rotation of the easy axis can partly account for the training effect and the recovery of the exchange bias.

PACS numbers: 75.30.Et, 75.30.Gw, 75.60.Jk

After exchange bias (EB) is established in ferromagnet (FM) /antiferromagnet (AFM) bilayers, hysteresis loop is shifted along the horizontal magnetic field axis by an amount of exchange field  $H_E$  [1, 2, 3, 4]. Meanwhile, the coercivity  $H_C$  is enhanced, compared with that of corresponding FM film. This phenomenon and other related physical properties have been studied extensively, including rotational hysteresis loss, training effect, asymmetrical magnetization reversal, and rotational hysteresis of angular dependence of EB [3, 5, 6].

In general,  $H_E$  and  $H_C$  shrink during subsequent measurements [3]. Although various theoretical models have been proposed to explain the training effect [7, 8, 9, 10, 11, 12, 13, 14], the mechanism is unsolved. For example, in an early approach [9, 15], the training effect is explained in terms of transition of spin orientation in AFM grains. Based on Mauri model, however, the training effect is ascribed to the irreversible motion of planar domain wall [11, 12]. Therefore, new experiments are required to establish a unique model of the training effect.

Up to date, hysteresis loops are always measured *at the easy axis* (EA) in studies of the training effect [15, 16]. At the EA, however, the magnetization reversal process in the FM layer is often accompanied only by motion of domain wall [5, 17]. In order to further reveal the nature of the training effect, hysteresis loops should also be measured along other orientations, at which the magnetization rotation occurs during magnetization reversal process, in addition to the motion of domain wall. More seriously, few other physical quantities have been measured in studies of training effect. Actually, since the orientation of AFM spins is altered during subsequent measurements of hysteresis loops [13], the orientation of the pinning field from the AFM layer, i.e., the EA of the FM layer is expected to rotate. In this Letter, we

have *for the first time* observed the EA rotation, accompanied by the training effect and the recovery of the EB in FM/AFM bilayers using FeNi/FeMn system. More remarkably, the EA rotation can in turn account for the training effect and the recovery of the EB.

A 1 cm  $\times$  5 cm bilayer of Fe<sub>20</sub>Ni<sub>80</sub>(=FeNi)(3 nm)/Fe<sub>50</sub>Mn<sub>50</sub>(=FeMn) was sputtered on glass substrate at ambient temperature. With a wedged shape across the distance of 5 cm, the FeMn layer thickness  $t_{AFM}$  is a linear function of the sampling location. A uniform bilayer of FeNi(3 nm)/FeMn (2.4 nm) was also prepared. A buffer layer of 15 nm Cu was used to stimulate the FCC (111) preferred orientation in FeMn layers and to enhance EB [18]. Finally, another 20 nm thick Cu layer was used to prevent oxidation. The EB was established by a magnetic field applied in the film plane during deposition. A detailed fabrication procedure was given elsewhere [6].

X-ray diffraction shows that constituent layers are polycrystalline with a strong FCC (111) peak and a weak FCC (200) one. Before magnetic measurements, the large specimen was cut into small pieces along the wedge direction. With a vector vibrating sample magnetometer (VVSM),  $m_x$  and  $m_y$  were measured, as components of magnetic moment parallel and perpendicular to the external magnetic field  $H_a$ , respectively. The  $m_x$  corresponds to conventional hysteresis loops.  $H_a$ ,  $m_x$ , and  $m_y$  are in the film plane. As torque curves,  $m_y$  were measured as a function of the  $H_a$  orientation [19]. Under  $H_a = 0$ , the EA can be identified as the angular position of  $m_y = 0$ . All measurements were performed at room temperature.

For convenience, we use  $\theta_H$  and  $\phi_{EA}$  to express the orientations of  $H_a$  and the EA with respect to the EA at the initial as-prepared state, respectively. For FeNi(3 nm)/FeMn(2.4 nm) bilayer, the EA at the initial state

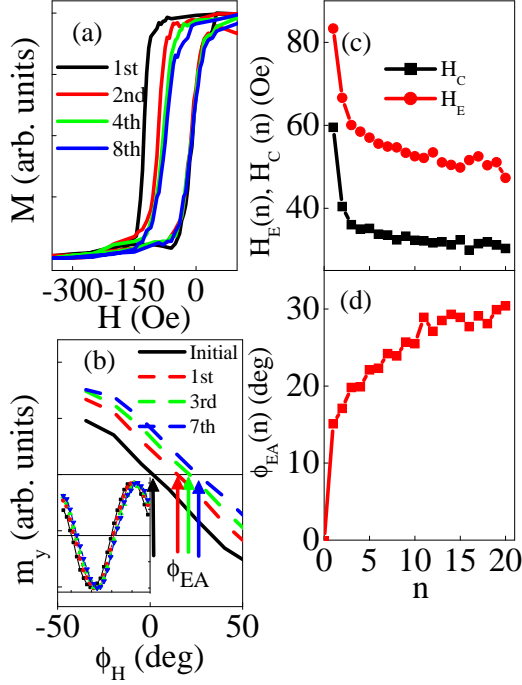


FIG. 1: Hysteresis loops (a) and angular dependence of  $m_y$  under  $H = 0$  with a small angular region (b), dependence of  $H_E$  and  $H_C$  (c) and of  $\phi_{EA}$  (d) on  $n$  for uniform FeNi(3 nm)/FeMn (2.4 nm) bilayers, where  $\theta_{H0} = -8$  degrees for measurements of hysteresis loops. In (b), arrows refer to  $\phi_{EA}$ . The inset shows the entire curve of  $m_y$  versus  $\theta_H$  under  $H = 0$ .

is at first identified. Then, hysteresis loops at a specific  $\theta_{H0}$  and torque curves with  $\theta_H$  from 0 to 360 degrees under  $H = 0$  were alternatively measured. Figure 1(a) shows hysteresis loops with subsequent measurements at  $\theta_{H0} = -8$  degrees. The coercivity of decent branch decreases significantly while that of ascent branch changes little with the cycle number  $n$ .  $H_E$  and  $H_C$  decrease with increasing  $n$ , as shown in Fig. 1(c). Although two subsequent hysteresis loops are interrupted by 3 minutes of torque measurements,  $H_E$  and  $H_C$  change in a scale of  $1/\sqrt{n}$ , except for  $n = 1$  [3]. Moreover, in experiments,  $m_y$  at the coercivity is found to increase with increasing  $n$  (not shown). For clarification, the torque curve, i.e., the angular dependence of  $m_y$  in a small region is shown in Fig. 1(b). Apparently, the position of  $m_y = 0$ , i.e.,  $\phi_{EA}$  is shifted towards high angles. This also agrees with the results that  $m_y$  at the coercivity increases with increasing  $n$  [20]. It should be noted that for the present FeNi/FeMn bilayers, the uniaxial anisotropy axis and unidirectional one are both aligned along the EA. This is because  $m_y$  is always equal to zero for hysteresis loops along the EA [21]. Figure 1(d) shows that  $\phi_{EA}$  at first increases sharply with increasing  $n$  and then approaches

saturation. Corresponding to much larger  $H_E(n = 1)$  and  $H_C(n = 1)$ ,  $\phi_{EA}(n = 0)$  is much lower than those with  $n \geq 1$ , as predicted by Hoffmann [7]. It is *the first time* that the EA in FM/AFM bilayers has been observed to rotate during subsequent measurements of hysteresis loops.

To further reveal the nature of correlation between the shrink of EB and the deviation of  $\phi_{EA}$ , the results in Figs. 1(c) & 1(d) are reorganized showing the dependence of  $H_E(n)$  and  $H_C(n)$  on  $\theta'_H$  as a function of  $n$ , where  $\theta'_H$  is the angle between  $H_a$  and the EA for the cycle number  $n$  and equals to  $\phi_{EA}(n - 1) - \theta_{H0}$  with  $\theta_{H0} = -8$  degrees. As shown in Fig. 2(a),  $H_E$  and  $H_C$  decrease with increasing  $\theta'_H$ . We also measured the conventional angular dependence of  $H_E$  and  $H_C$  on the orientation of  $H_a$  for FeNi(3 nm)/FeMn (2.4 nm) bilayers. For comparison, the angular dependence is shown within the region from 0 to 90 degrees, as shown in Fig. 2(b). The variation of  $H_E(n)$  and  $H_C(n)$  with  $\theta'_H$  agrees with the angular dependence of  $H_E$  and  $H_C$  merely qualitatively. Since the deviation of the EA cannot account for the training effect very well, however, effect of the exchange coupling energy between FM and AFM layers and uniaxial anisotropy energy should be considered, changes of which with  $n$  were observed in our experiments [? ].

Here, we define  $\Delta H_{E/C}/H_{E/C}(n = 1)$  to express the relative change of  $H_E$  and  $H_C$  in training effect, where  $\Delta H_{E/C} = H_{E/C}(n = 1) - H_{E/C}(n = 20)$ . In a similar way, we have  $\Delta\phi = \phi_{EA}(n = 20) - \phi_{EA}(n = 0)$ . Actually, for  $n > 20$ , the changes of  $H_E$ ,  $H_C$ , and  $\phi_{EA}$  are negligible, as shown in Fig. 1. Figures 3(a) & 3(b) show the angular dependence of the relative changes of  $H_E$  and  $H_C$  and of  $\Delta\phi$  for typical bilayer of FeNi(3 nm)/FeMn(2.4 nm). Firstly, as conventional results [3, 15], the training effect still exists at  $\theta_H = 0$  although  $\Delta\phi = 0$ . Apparently, the training effect is caused by the changes of the unidirectional and uniaxial anisotropy energies instead of the EA rotation. Secondly, at high  $\theta_H$ , the training effect increases as  $\Delta\phi$  is increased as a function of  $\theta_H$ . Figures 3(c) & 3(d) show  $\Delta H_E/H_E(n = 1)$ ,  $\Delta H_C/H_C(n = 1)$ , and  $\Delta\phi$  as a function of  $t_{AFM}$  at a specific  $\theta_{H0} = -12$  degrees for FeNi (3 nm)/FeMn bilayers.  $\Delta H_E/H_E(n = 1)$ ,  $\Delta H_C/H_C(n = 1)$ , and  $\Delta\phi$  change in similar variation trends. These scenario correlations indicate that the training effect is mainly caused by the EA rotation in the frame of the angular dependence of  $H_E$  and  $H_C$  in Fig. 2(b).

For polycrystalline AFM layers, AFM grains are aligned randomly in the film plane. For FeMn layers with (111) preferred orientation, AFM grains have multi-easy axis anisotropy [7, 22]. After field-cooling procedure or at the as-prepared state under an external magnetic field, AFM spins are expected to be aligned along an EA close to the cooling field or the deposition magnetic field. Assuming no interaction between AFM grains [6, 9], AFM grains are suggested to have transitions from non-

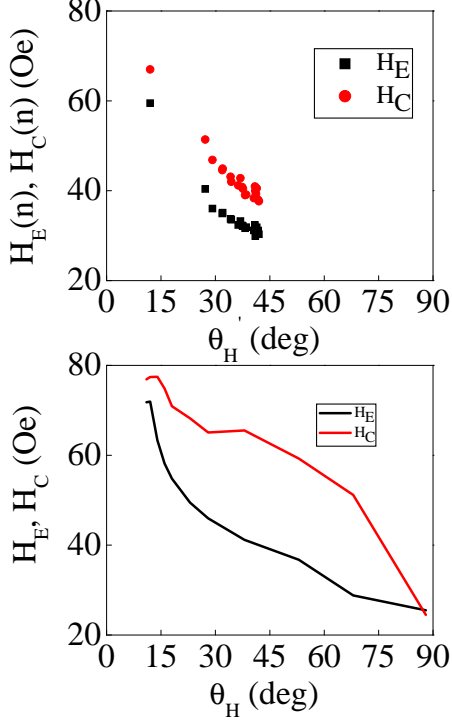


FIG. 2: For uniform FeNi(3 nm)/FeMn (2.4 nm) bilayer,  $H_C(n)$  and  $H_E(n)$  versus  $\theta'_H$  (a), and the dependence of  $H_C$  and  $H_E$  on  $\theta_H$  (b). In (a)  $\theta'_H = \phi_{EA}(n-1) - \theta_{H0}$  and  $\theta_{H0} = -8$  degrees.

equilibrium to equilibrium states triggered by subsequent measurements of hysteresis loops [13, 16]. As the AFM spins of some grains have transition from one EA to another one, the orientations of unidirectional and uniaxial anisotropies are rotated [23]. Meanwhile, their magnitudes might also change. Therefore,  $H_C$  and  $H_E$  at specific  $\theta_H$  should shrink with  $n$ .

In thin AFM layers, most of AFM grains are "superparamagnetic" and the EB disappears [6, 24]. Hence, the training effect and the deviation of the EA are equal to zero. At the intermediate AFM layer thickness, most of AFM grains are thermally stable, including rotatable and non-rotatable ones [25]. Since a large fraction of AFM grains can be rotated irreversibly, the deviation of the orientation of the effective pinning field reaches maximum, so does the training effect. As  $t_{AFM}$  is further increased, the volume of AFM grains and the anisotropy energy barrier increase, resulting in a reduction of transition possibility. The deviation of the EA and the training effect are suppressed.

At  $\theta_H = 0$ , the magnetization reversal process is accompanied only by the motion of domain wall [5, 20]. AFM spins can only be switched by an angular amount of 180 degrees [17] and the pinning field is still aligned

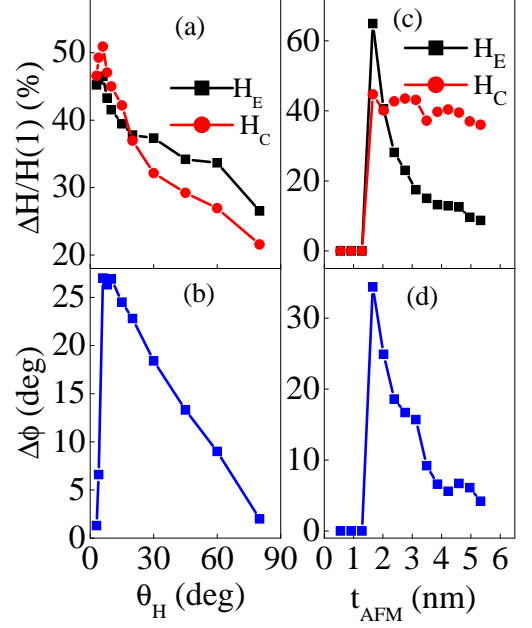


FIG. 3: Dependence of  $\Delta H_E/H_E(n=1)$  and  $\Delta H_C/H_C(n=1)$  (a, c) and  $\Delta\phi_{EA}$  (b, d) on  $\theta_H$  for uniform FeNi(3 nm)/FeMn (2.4 nm) bilayer (a, b) and  $t_{AFM}$  at  $\theta_{H0} = -12$  degrees for FeNi(3 nm)/wedged-FeMn (0-6.25 nm) bilayers (c, d).

along that of the initial state and thus  $\phi_{EA} = 0$ , as shown in Fig. 3(b). As  $H_a$  is deviated away from the initial EA, the magnetization reversal process is accompanied by both motion of domain wall and magnetization rotation and finally by magnetization coherent rotation for large  $\theta_H$  [5, 20]. Since AFM spins can be rotated from one EA to other one, in addition to the 180-degree switching, the EA can be deviated from that of the initial state. With the FM magnetization rotation, the transition possibility, thus the relative change of the EB and  $\Delta\phi$  are enhanced [17], compared with those of 180-degree switching. As  $\theta_H$  is further increased, the magnetization reversal process for ascent and descent branches is almost symmetric [5]. In this case, contributions of transition possibility in the two pathways are cancelled so that the deviation of the EA and thus the training effect are reduced. In a word,  $\Delta\phi$  strongly depends on  $\theta_H$  because the mechanism of the motion of AFM spins is determined by the magnetization reversal mechanism of the FM layer. This latter in turn depends on  $\theta_H$ .

Although the EB recovery has been studied more recently [16], observation of the EA during the EB recovery can elucidate the nature of this phenomenon. Here, the EB recovery in FeNi(3 nm)/FeMn (2.4 nm)

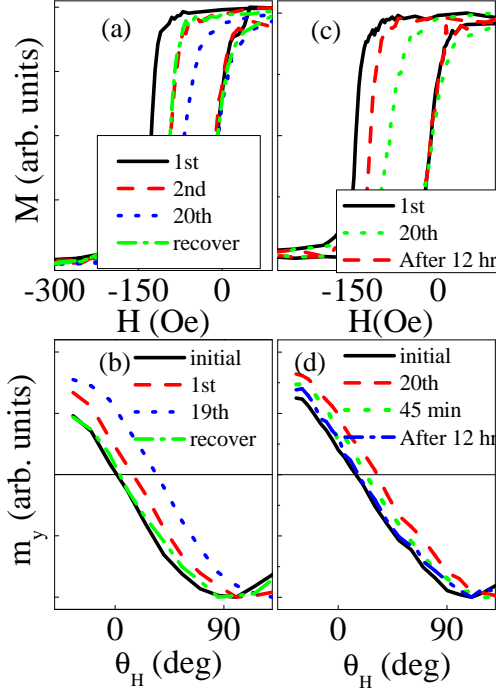


FIG. 4: Hysteresis loops at  $\theta_{H0} = -8$  degrees (a,c) and angular dependence of  $m_y$  under  $H = 0$  (b,d) using the first (a,b) and the second (c,d) recovery methods for uniform FeNi(3 nm)/FeMn (2.4 nm) bilayers.

bilayers is studied using two different methods. As the first method [16], after subsequent measurements of hysteresis loops at  $\theta_{H0} = -8$  degrees, a hysteresis loop was measured at an orientation perpendicular to  $\theta_{H0} = -8$ . After that, a hysteresis loop was measured again at  $\theta_{H0} = -8$  degrees. As the second spontaneous method, after  $H_C$  and  $H_E$  are stable with subsequent measurements of hysteresis loops,  $H_a$  is set to zero for a designated period. Then, hysteresis loops and torque curves were measured. In this way,  $H_C$ ,  $H_E$ , and  $\phi_{EA}$  are achieved at different waiting time. Figures 4(a) & 4(c) show that with either recovery method,  $H_C$  and  $H_E$  are increased, compared with those of  $n = 20$ . Meanwhile, after the recovery procedure, the EA approaches back towards that of the initial state, as shown in Figs. 4(b) & 4(d). Therefore, the variation of  $\phi_{EA}$ , partly accounting for the EB recovery, *directly* verifies the micro-magnetic calculations that the orientation of AFM spins are rearranged after recovery procedure [16]. For CoO/Co bilayers, the orientation of AFM spins is argued to change with respect to the cooling field during training effect and recovery of the EB.

In summary, the EA in FM/AFM bilayers has been *for the first time* found to vary during the shrink and

recovery of the EB using FeNi/FeMn system. For AFM spins, the irreversible motion of 180-degree switching or coherent rotation, depending on the magnetization reversal mechanism of the FM layer, is unambiguously demonstrated during measurements of hysteresis loops. The training effect and  $\Delta\phi$  vary in a similar way with either  $\theta_H$  or  $t_{AFM}$ . Furthermore, the EA is rotated back towards that of the initial state during the EB recovery. Therefore, the EA rotation is one of the major reason for the training effect and the recovery of the EB for large  $\theta_H$ .

**Acknowledgement** This work was supported by the National Science Foundation of China Grant Nos. 50625102, 10574026, and 60490290, the National Basic Research Program of China (2007CB925104) and 973-Project under grant no. 2006CB921300, Shanghai Science and Technology Committee Grant No. 06DJ14007.

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